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Short-rotation forestry of birch, maple, poplar and willow in Flanders (Belgium) I—Biomass production after 4 years of tree growth

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Abstract

During the last three decades, oil crises, agricultural surpluses and global climate change enhanced the interest in short-rotation forestry (SRF). In this study, the biomass production of birch (*Betula pendula* Roth), maple (*Acer pseudoplatanus* L.—Tintigny), poplar (*Populus trichocarpa* × *deltoides*—Hoogvorst) and willow (*Salix viminalis*—Orm) growing under a short-rotation (SR) management system were compared after a 4 years period. The plantation was established on former agricultural land. The sandy soil had a mean pH of 4.5 and a mean carbon content of 1.0%. Survival rates after 4 years were 75.8%, 96.8%, 86.3% and 97.6% for birch, maple, poplar and willow, respectively. The mean actual annual biomass production for these four species amounted to 2.6, 1.2, 3.5 and 3.4 t DM $ha^{-1} yr^{-1}$, respectively. The large variation in biomass production at the different plots of the plantation could not be explained by the measured soil parameters. Biomass production results found here were in the lower range of values reported in literature. However, in contrast to most other studies, no weed control, fertilisation or irrigation was applied in this experiment. As marginal agricultural soils are suboptimal for the growth of poplar and willow, birch can be considered as a very interesting alternative for the establishment of SR plantations in Flanders.

Keywords: Allometric relations; Biomass production; Birch; Maple; Poplar; Short-rotation forestry; Survival rate; Willow

1. Introduction

Since the energy crisis of the 1970s, many European countries have shown an increased interest in renewable energy sources. The use of biomass produced by either crops or short-rotation (SR) plantations was one of the options studied at that time [1]. In the late 1980s, the large agricultural surpluses in Western Europe had to be reduced, which resulted in large areas of land being released from agricultural production. The establishment of SR plantations on this arable land therefore fits in the European set-aside policy. The growing concern about the consequences of burning fossil fuels on the global climate system enhanced the attention for short-rotation forestry (SRF) during the last decade. Under the Kyoto Protocol, the European Union committed itself to an 8% reduction in annual greenhouse gas emissions by the first commitment period (2008–2012), compared to the reference year 1990 [2]. The 'White Paper of the European Commission on renewable sources of energy' [3] gave a clear political signal by setting the target at increasing the renewable energy sources, including biomass, to reach 12% of the European gross energy consumption by 2010. This is a doubling compared to the situation in 1997 [3,4]. An extensive literature review showed that it can be expected that in the future, bio-energy plantations will become the most important source of biomass for energy on a global scale [5]. In SR forestry systems, fast-growing species are grown to attain high yields of biomass. Highest yields are obtained under intensive management systems, including weed control, fertilizer application and irrigation [1,6–9].

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From a survey executed by Meiresonne et al. (personal communication), it appeared that, in principle, the Flemish farmers are not against the implementation of SRF on their former fields. However, it becomes clear though that farmers, willing to introduce plantations of woody biomass, will certainly not use their best agricultural soils for this purpose. This is an important element in the choice of a suitable species to be used in biomass plantations. It can be expected that the water and nutrient status of these marginal fields will not be optimal at all.

Most often, poplar and willow are recommended for planting in SR systems. Some research focussed on the use of birch [10–14] and alder [12,15,16]. In this study, four tree species were used. Poplar and willow were selected as the most frequently used species in SR plantations, while birch and maple represented possible alternatives. Birch is an indigenous species in Flanders, while both birch and maple, two shade-intolerant species, are known to have a high regeneration capacity and a high growth rate, even on poor soils. In this paper, the aboveground biomass production of the four tree species under a SR forestry system were compared after 4 years of tree growth, and production results of this plantation were compared to results from other (European) studies. In a joint paper [17], the possible contribution of SRF biomass to the total electricity production in Flanders was determined, and the potential of SRF plantations to reduce the CO_2 emissions in this region was assessed.

2. Material and methods

2.1. SR plantation

In March and April 2001, a SR plantation was established on former agricultural land by hand planting. The site is situated at Zwijnaarde (51°02′N, 3°43′E), which is 10 km south of the centre of Ghent (Belgium). The site is characterised by a temperate maritime climate, with moderate temperature variation, prevailing westerly winds, a heavy cloud cover and regular rainfall. Long-term mean values for the mean air temperature and the annual amount of rainfall are 9.8 °C and 821 mm, respectively. At the start of the experiment, the upper 30 cm layer of the sandy soil had a mean organic carbon concentration of 1.0% and a pH_{KCl} of 4.5. The total area of the plantation is 8800 m^2, and is composed of 22 plots of 400 m^2 each (25×16 m). Birch (*Betula pendula* Roth), maple (*Acer pseudoplatanus* L.—Tintigny), poplar (*Populus trichocarpa* × *deltoides*—Hoogvorst) and willow (*Salix viminalis*—Orm) were planted on four, three, eight and seven plots, respectively. Birch and maple were planted as 2-year-old saplings, with a density of 6667 stems ha^{-1} (spacing distance: 1.0×1.5 m), while 20 cm unrooted cuttings of poplar and willow were planted with an initial density of 20,000 stems ha^{-1} (spacing distance: 1.0×0.5 m). The plantation activity was preceded by tillage of the upper 20 cm of the soil. Afterwards, no specific management activities such as weed control, fertilisation or irrigation were performed in the plantation. As such, biomass production was examined under non-ideal growing conditions, and the SRF system can be considered as an extensively managed plantation.

2.2. Allometric relations

At the end of 2003, site- and species-specific allometric relationships were established by destructive sampling of a number of trees per species and per diameter class. Trees were cut at a height of 10 cm. Stems and branches were dried until constant weight. Allometric relations of the form aboveground dry mass ($AGDM$) $= ad_{30}^b$ were established for each species, with $AGDM$ dry mass of stems and branches (in g DM) and d_{30} the diameter at 30 cm (in mm). This power function is biologically reasonable and in accordance to literature [1,18–20]. The number of trees harvested per species and the values for the coefficients a and b are shown in Table 1. The adjusted R^2-values were as high as 0.98 for all four species.

2.3. Aboveground biomass production

In January 2005, the diameter at 30 cm height (d_{30}) of 20 randomly chosen trees per plot was measured with a mechanical calliper. Trees growing in the outer two rows were excluded from the measurements in order to reduce edge effects. The allometric relations described above were used to convert the diameter d_{30} in the total $AGDM$ of the tree.

The potential and the actual biomass production of each plot were calculated according to

$$PROD = \frac{(AGDM_{\text{mean}} - PDM_{\text{mean}})}{1,000,000} D, \tag{1}$$

with $PROD$, biomass production of the plot (t DM ha^{-1}); $AGDM_{\text{mean}}$, mean aboveground dry mass per tree for a specific plot, determined in January 2005 (g DM $tree^{-1}$); PDM_{mean}, mean planted aboveground dry mass per tree, determined in March or April 2001 (g DM $tree^{-1}$); D, stem density of the plot (trees ha^{-1}); and 1,000,000, conversion factor from g DM to t DM.

For poplar and willow, which were planted as cuttings, the mean planted dry mass, PDM_{mean}, was equal to zero.

Table 1
Number of sample trees (n), regression coefficients a and b (with standard error between brackets) of the allometric power equation $AGDM = a.d_{30}^b$, with $AGDM$: aboveground dry mass of the tree (g DM) and d_{30}: diameter at 30 cm (mm)

Species	n	a	b	Adjusted R^2
Birch	18	0.292 (0.078)	2.242 (0.078)	0.980
Maple	49	0.067 (0.088)	2.662 (0.050)	0.983
Poplar	18	0.295 (0.076)	2.223 (0.077)	0.980
Willow	34	0.135 (0.022)	2.553 (0.059)	0.983

PDM_{mean} was 3.0 and 5.1 g DM tree^{-1} for birch and maple, respectively.

To calculate the potential biomass production $PROD_{pot}$, D equalled the initial tree density D_{ini} (6667 trees ha^{-1} for birch and maple, 20,000 trees ha^{-1} for poplar and willow). The actual biomass production $PROD_{act}$ of the different plots was calculated based on the actual tree density D_{act}. This actual density was determined in the field in January 2005, by counting all surviving trees per plot. The survival rate (SR) per plot was calculated as the ratio between D_{act} and D_{ini}, expressed in terms of percentage.

3. Results

3.1. Diameter d_{30} and aboveground dry mass $AGDM$

In Table 2, the mean diameter at 30 cm d_{30} and the mean $AGDM$ per tree is given for all plots of the SR plantation at Zwijnaarde. There were no results available for plot 2. For willow, there was a negative relation between the mean diameter and the number of shoots: the highest mean diameters were found in the plots with the lowest mean number of shoots per tree. ANOVA and post-hoc tests (Duncan and Tamhane's test) (SPSS 11.5) revealed significant differences in d_{30} between plots for all four species. Regarding the $AGDM$, no significant differences were found between the four birch plots (Table 2), while for the other species, two (maple and poplar) or more (willow) groups of plots could be distinguished.

3.2. Potential and actual biomass production

The annual potential ($PROD_{pot}$) and actual biomass production ($PROD_{act}$) after 4 years of tree growth are listed in Table 3 for all plots. Survival rates of more than 90% were noted for all maple and willow plots (Table 3), which resulted in a very good agreement between the potential and actual biomass production values for the plots of these two species. For birch and poplar, the mean actual biomass production was clearly lower than the potential one, because of the lower survival rates (mean of 75.8% for birch, and 86.3% for poplar). As can be concluded from the same table, a large within-species heterogeneity of biomass production was observed.

ANOVA combined with post-hoc tests (Duncan) revealed a significantly lower mean potential biomass production of maple (1.2 t DM ha^{-1} yr^{-1}) compared to birch (3.3 t DM ha^{-1} yr^{-1}), willow (3.5 t DM ha^{-1} yr^{-1}) and poplar (4.2 t DM ha^{-1} yr^{-1}). On the other hand, the actual biomass production of maple (1.2 t DM ha^{-1} yr^{-1}) and

Table 2
Mean diameter at 30 cm height (d_{30}) and mean aboveground dry mass per tree ($AGDM$) for all plots of the SRF plantation at Zwijnaarde after four growing seasons; s.e. on the mean is given between brackets

Species	Plot nr.	Mean d_{30} (mm)	Mean $AGDM$ (g DM tree^{-1})
Birch	4	49.0 (2.9)^{a,b}	1968 (284)^{a}
	5	46.8 (3.1)^{a}	1810 (262)^{a}
	8	56.2 (3.1)^{b}	2636 (314)^{a}
	11	45.2 (2.5)^{a}	1616 (183)^{a}
Maple	13	25.2 (1.4)^{a}	401 (56)^{a}
	18	32.5 (1.7)^{b}	787 (96)^{b}
	22	35.4 (2.2)^{b}	1025 (147)^{b}
Poplar	1	29.0 (1.3)^{a}	552 (52)^{a}
	6	29.7 (3.4)^{a,b}	749 (197)^{a,b}
	9	33.2 (1.4)^{a,b}	745 (71)^{a,b}
	12	39.4 (1.5)^{b}	1079 (89)^{b}
	16	38.5 (2.0)^{b}	1073 (116)^{b}
	17	32.4 (3.0)^{a,b}	820 (158)^{a,b}
	20	34.7 (2.9)^{a,b}	918 (153)^{a,b}
	21	31.7 (2.1)^{a,b}	709 (84)^{a,b}
Willow[x]	3	11.6 (0.6)^{a}	283 (37)^{a}
	7	15.6 (1.0)^{b}	523 (65)^{b}
	10	24.0 (1.1)^{d}	1170 (125)^{d}
	14	21.5 (1.2)^{c,d}	870 (142)^{b,c,d}
	15	18.0 (1.1)^{b,c}	771 (91)^{c}
	19	20.1 (1.0)^{c,d}	606 (75)^{b,c}

Measurements were performed in January 2005. Different letters indicate significant differences between d_{30} or $AGDM$ of the plots for a specific species ($p = 0.05$).
[x]Number of shoots was 59, 50, 44, 42, 51 and 36 for the plots 3, 7, 10, 14, 15 and 19, respectively.

Table 3
Survival rate SR, potential ($PROD_{pot}$) and actual biomass production ($PROD_{act}$) of all plots of the SRF plantation at Zwijnaarde after 4 years of tree growth

Species	Plot nr.	SR (%)	$PROD_{pot}$ (t DM ha^{-1} yr^{-1})	$PROD_{act}$ (t DM ha^{-1} yr^{-1})
Birch	4	69.5	3.3	2.3
	5	69.5	3.0	2.1
	8	83.5	4.4	3.7
	11	80.8	2.7	2.2
	Mean	*75.8*	*3.3*	2.6
Maple	13	93.8	0.7	0.6
	18	97.7	1.3	1.3
	22	98.9	1.7	1.7
	Mean	*96.8*	*1.2*	1.2
Poplar	1	94.9	2.8	2.6
	6	81.3	3.7	3.0
	9	95.4	3.7	3.6
	12	92.9	5.4	5.0
	16	68.3	5.4	3.7
	17	77.9	4.1	3.2
	20	85.4	4.6	3.9
	21	94.7	3.5	3.4
	Mean	*86.3*	*4.2*	3.5
Willow	3	97.1	1.4	1.4
	7	98.4	2.6	2.6
	10	98.5	5.9	5.8
	14	98.9	4.4	4.3
	15	97.5	3.9	3.8
	19	95.0	3.0	2.9
	Mean	*97.6*	*3.5*	*3.4*

birch (2.6 t DM ha^{-1} yr^{-1}) were significantly lower than the $PROD_{act}$ of willow (3.4 t DM ha^{-1} yr^{-1}) and poplar (3.5 t DM ha^{-1} yr^{-1}).

4. Discussion

4.1. Individual tree growth

Ferm [21] reported a mean diameter of 92 mm in a *B. pendula* energy stand in Finland after 14 years of tree growth, for a density of 6475 stems ha^{-1}. This diameter is larger than the value found in Zwijnaarde after a rotation period of 4 years. However, comparison is difficult as the measuring height is not indicated in the Finnish study [21]. In a study on eight poplar and two willow clones, Bungart and Hüttle [22] found a mean diameter range (height undefined) from 20 to 41 mm after 4 years of tree growth. Values found for poplar and willow in Zwijnaarde were comparable to these results (Table 2).

In a Swedish study [12], the mean weight of an individual birch tree after four growing seasons was 1247–1522 g DM; values found here (Table 2) were slightly higher. Individual values of tree biomass production of poplar clones ranged from 1231 to 4226 g DM $tree^{-1}$ in the study of Telenius [12], while Barigah et al. [23] found a mean *AGBM* between 111 and 408 g DM $tree^{-1}$ for five poplar clones during their establishment year. Values found in Zwijnaarde after 4 years of tree growth were situated in between these results. Bergkvist and Ledin [18] reported for *S. viminalis* a mean dry weight between 1000 and 2200 g DM $stool^{-1}$ after 4 years of tree growth. The mean tree dry weight of *S. fragilis* was 1256 g DM in the Swedish study of Telenius [12], while a value of 1000–2100 g DM $tree^{-1}$ was found for a coppiced willow plantation in Ireland [24], with a planting density identical to the one in Zwijnaarde, and after a 3 years growing period. Nordh and Verwijst [20] reported tree dry mass values for different willow clones between 1600 and 2070 g DM $tree^{-1}$ after 4 years of tree growth. Except for plot 10, values found in Zwijnaarde were considerably lower than these literature values (Table 2). Possible causes of the mentioned differences are discussed below.

4.2. Survival rate

Both maple and willow had a very high survival rate, in all plots (Table 3). The low mean survival rate of birch (mean of 75.8%) was mainly caused by the dieback of a number of birches during the first year, caused by the exposure of the root systems to strong wind and cold temperatures at the moment of tree planting. Unfortunately, we were not able to replant these trees later on. The mean survival rate for poplar was 86.3%, but ranged from 68.3% in plot 16 to 95.4% in plot 9. Some of the poplar plots suffered severely from an infection of *Colletotrichum gloeosporioides*. As such, a number of poplars died during the 4 years of the experiment. However, the survival rates in Zwijnaarde were higher than most results found in literature [18,20,25,26]. The poplars in Zwijnaarde had a very high and uniform survival rate during the establishment year, as was also reported by Ceulemans and Deraedt [7]. These authors [27] also mentioned an infection of poplar species with rust and other pathogens, in a SR plantation situated in Boom, at a distance of 60 km from our study site.

4.3. Intra-species variation in biomass production

As indicated in Table 3, there was a large variation in biomass production between the different plots of the four species. These differences in production were possibly due to a large heterogeneity of the soil physical and soil chemical characteristics, as is also mentioned by Tahvanainen and Rytkönen [1] and Venendaal et al. [28]. To test this hypothesis, a number of abiotic soil parameters were studied. These comprised the carbon (%) and nitrogen content (ppm), the C:N ratio, the pH_{KCl} and the bulk density (g cm^{-3}) of the soil layers 0–5, 5–15, 15–30, 30–50 and 50–100 cm; mean values of these parameters were also calculated for the layers 0–30, 0–50 and 0–100 cm [29]. However, neither regression analysis nor PCA resulted in a significant relation between one or more of these soil parameters and the potential or actual biomass production of one of the tree species. This means that probably other characteristics, which were not measured, caused the variation in biomass production. These can include parameters related to micro-scale differences in soil water content or other element concentrations than the ones measured. Tahvanainen and Rytkönen [1] stated that there were also non-climatic and non-soil-related factors which had an influence on the biomass production of *S. viminalis* clones in their study. However, our results confirmed the findings of Laureysens et al. [19], who found no clear relation between the production of 17 poplar clones, among which the clone 'Hoogvorst', and a whole range of soil characteristics.

4.4. Comparison of the biomass production in Zwijnaarde to other European sites

Most biomass production results of SRF systems described in literature refer to poplar or willow plantations [1,6,8,12,18–20,22,23,25–27,30–32], only a few are related to birch plantations [10,12,13], and no results were found for maple, except for the reference by Ceulemans et al. [33] to unpublished results. In general, biomass production results for poplar are in the range between 10 and 15 t DM ha^{-1} yr^{-1}, while for willow, a range from 10 to 12 t DM ha^{-1} yr^{-1} is most often referred to [33]. Some extremely high productivity numbers are also quoted: 27.5 t DM ha^{-1} yr^{-1} for a new hybrid poplar clone under optimal conditions, 28.5 t DM ha^{-1} yr^{-1} for *S. viminalis* in Canada and 36 t DM ha^{-1} yr^{-1} for *Salix dasyclados* in intensively irrigated and fertilised small plots in Sweden.

However, in practise, biomass production is often lower than these potential values [33].

In Table 4, the mean actual biomass production $PROD_{act}$ of birch in Zwijnaarde is compared to results from other European studies; only results for a rotation length of at least 4 years were presented. Table 5 gives an overview of production results for poplar; here, only results from European studies were selected, from a first rotation with a minimum length of 4 years and a minimum planting density of 5000 trees ha^{-1}; results from plantations on peat soils were not listed. Results from European *S. viminalis* plantations can be found in Table 6; the same restrictions as for the poplar plantations were applied. From these three tables, it can be concluded that the results found in Zwijnaarde fell in the lower range of the results from other European studies. However, in SRF plantations, cultural factors such as planting density, rotation length, fertilisation and irrigation all affect biomass production [8]. Moreover, site characteristics as soil type and climate also result in different production potentials.

4.4.1. Planting density and rotation length

Optimal planting densities recommended for willow are 10,000–20,000 trees ha^{-1} [18,30,34], while Ceulemans and Deraedt [7] stated that for poplar SRF plantations, optimal densities range from 2500 to 10,000 trees ha^{-1}. Optimum rotation time for poplar and willow SR forestry seems to be 4 or 5 years [7,34]. Planting densities used in Zwijnaarde were 20,000 trees ha^{-1} for both poplar and willow, and results were calculated after a 4 years rotation length. As such, there is no reason to suspect that one of these two factors will have caused the low biomass production of poplar and willow. Hytönen and Issakainen [13] reported that the highest mean annual biomass production of downy birch (*B. pubescens*) was found for rotation lengths of 8 years and more, while the highest values listed in Table 4 were found for a rotation period of 12 years [10]. This leads us to suspect that after the rotation length of only 4 years, the mean annual biomass production of birch in Zwijnaarde is not at its maximum yet, and will enhance if the rotation length will increase. Moreover, sowing birches instead of planting them could enhance the tree density compared to the density applied in Zwijnaarde (6667 trees ha^{-1}). A higher tree density combined with a longer rotation period will most probably improve the biomass production of birch.

4.4.2. Weed control and fertilisation

In most studies reported in Tables 4–6, herbicides and/or fertilizers were applied. Weed control is indicated as an important factor during the establishment phase of SRF plantations [34,35]. Although the use of fertilizers is advised by some authors [30,34], fertilisation did not always result in a higher biomass production [12,26,31]. The response on nutrients in soils and fertilizers is strongly dependent on a large variety of factors. Nutrient amounts in the soil from former land use, soil texture, rooting behaviour, moisture availability and specific clone or cultivar properties will effect growth and nutrition of the stand, and therefore, have to be considered [30]. The regular removal of woody biomass may require additional fertilizers to be added, to maintain soil fertility and to sustain high production rates [22,35]. If we would have applied chemical or mechanical weed control, biomass production could have been somewhat higher. However, the use of additional fertilizers will probably not have affected the production rates in Zwijnaarde to a large extent, as the plantation was established on former

Table 4
Biomass production of European SRF plantations of birch

Species	Country	Soil type	pH	Management	Planting density (trees ha^{-1})	Rotation length (y)	Biomass production (t DM ha^{-1} yr^{-1})	Reference
1	F	Peat	n.i.	n.i.	30,000	4	0.5	[13]
1	F	Peat	n.i.	n.i.	30,000	8 (2 × 4)	0.7	[13]
1	F	Peat	n.i.	n.i.	33,000	4	1.2	[13]
1	F	Peat	n.i.	n.i.	30,000	8	1.3	[13]
1	F	Peat	n.i.	n.i.	33,000	8 (2 × 4)	1.5	[13]
1	F	Peat	n.i.	n.i.	30,000	12	1.7	[13]
1	F	Peat	n.i.	n.i.	30,000	16	1.9	[13]
2	S	Clay	6–7	W	5000	6	2.3	[12]
1	F	Peat	n.i.	n.i.	33,000	8	2.6	[13]
2	B	Sand	4.5	None	6667	4	2.6	This study
3	A	Brown soil	5.4	None	3333	12	3.7	[10]
3	A	Brown soil	5.4	None	4444	12	4.2	[10]
3	A	Brown soil	5.4	None	10,000	12	5.6	[10]
3	A	Brown soil	5.4	F	3333	12	5.9	[10]
3	A	Brown soil	5.4	F	4444	12	6.1	[10]
3	A	Brown soil	5.4	F	10,000	12	7.3	[10]

Species code 1: *Betula pubescens*, 2: *Betula pendula*, 3: *Betula verrucosa*; country code A: Austria, B: Belgium, F: Finland, S: Sweden; management code W: weed control, F: fertilizers; n.i.: no information.

Table 5
Biomass production of European SRF plantations of poplar

Species	Country	Soil type	pH	Management	Planting density (trees ha^{-1})	Rotation length (y)	Biomass production (t DM ha^{-1} yr^{-1})	Reference
D × N	B	Loam/sandy-loam	7.3—.0	W	10,000	C + 4	2.2	[19]
—[a]	D	Sand	7.2–7.7	F	8333	4	2.3[a]	[22]
D × T	B	Loam/sandy-loam	7.3–8.0	W	10,000	C + 4	2.8	[19]
Ta × To	D	Sand	n.i.	None	5000	5	3.0	[30]
Ta × To	D	Sand	n.i.	F	8333	5	3.0	[30]
Ta × To	D	Sand	n.i.	F	5000	5	3.2	[30]
T × D	B	Sand	4.5	None	20,000	4	3.5	This study
Ta × To	D	Sand	n.i.	None	8333	5	3.6	[30]
D × T	B	Loam/sandy-loam	7.3–8.0	W	10,000	C + 4	3.6	[19]
T × D	B	Loam/sandy-loam	7.3–8.0	W	10,000	C + 4	3.7	[19]
D × T	B	Loam/sandy-loam	7.3–8.0	W	10,000	C + 4	3.7	[19]
T	D	Sand	n.i.	F	8333	5	3.7	[30]
T	D	Sand	n.i.	F	16,667	5	4.1	[30]
D × N	B	Loam/sandy-loam	7.3–8.0	W	10,000	C + 4	4.7	[19]
T	D	—[b]	n.i.	None	16,667	5	4.8[b]	[30]
T	D	Sand	n.i.	None	8333	5	4.8	[30]
T × B	B	Loam/sandy-loam	7.3–8.0	W	10,000	C + 4	4.8	[19]
Ta × To	D	Sandy clay	n.i.	None	16,667	5	5.2	[30]
D × N	B	Loam/sandy-loam	7.3–8.0	W	10,000	C + 4	5.2	[19]
Ta × To	D	Sandy clay	n.i.	F	16667	5	5.5	[30]
T × D	B	Loam/sandy-loam	7.3–8.0	W	10000	C + 4	5.8	[19]
T	D	Sandy clay	n.i.	F	16,667	5	5.9	[30]
T × D	B	Loam/sandy-loam	7.3–8.0	W	10,000	C + 4	5.9	[19]
T × D	GB	Heavy clay loam	n.i.	W	10000	C + 4	6.4	[25]
T × D	B	Loam/sandy-loam	7.3–8.0	W	10,000	C + 4	6.6	[19]
T × D	S	Clay	6–7	W	5000	6	7.3	[12]
T	GB	Heavy clay loam	n.i.	W	10,000	C + 4	7.5	[25]
T × D	S	Clay	6–7	W	5000	6	7.6	[12]
T	B	Loam/sandy-loam	7.3–8.0	W	10,000	C + 4	8.0	[19]
T × D	GB	Heavy clay loam	n.i.	W	10,000	C + 4	8.1	[25]
N	B	Loam/sandy-loam	7.3–8.0	W	10,000	C + 4	8.2	[19]
T	B	Loam/sandy-loam	7.3–8.0	W	10,000	C + 4	8.3	[19]
T	B	Loam/sandy-loam	7.3–8.0	W	10,000	C + 4	8.5	[19]
T	GB	Argilic brown earth	n.i.	W	10,000	C + 4	9.2	[25]
—[c]	B	Loam/sandy-loam	7.3–8.0	W	10,000	C + 4	10.1[c]	[19]
T × D	B	Loam/sandy-loam	7.3–8.0	W	10,000	C + 4	10.4	[19]
T × D	B	Loam/sandy-loam	7.3–8.0	W	10,000	C + 4	11.4	[19]
T × D	GB	Argilic brown earth	n.i.	W	10,000	C + 4	12.8	[25]
T × D	GB	Argilic brown earth	n.i.	W	10,000	C + 4	13.6	[25]

Species refers to the parentage of the poplar clone used: B, *P. balsamifera*; D, *P. deltoides*; N, *P. nigra*; T, *P. trichocarpa*; Ta, *P. tremula*; To, *P. tremuloides*; country code B, Belgium; D, Germany; GB, England; S, Sweden; management code W, weed control; F, fertilizers; rotation length, C means coppiced after establishment year; n.i., no information.

[a]Mean of eight poplar clones.

[b]Mean of two sites.

[c]Mixture of clones.

agricultural land, and we only studied the first rotation cycle.

4.4.3. Soil characteristics

The optimal pH for the growth of poplar and willow ranges from 5 to 7.5 [1,27,34,35]. The mean pH of the top soil in Zwijnaarde was only 4.5, a value lower than this optimal range. Poplar and willow are known to be species with a high water requirement, and often, water availability is the limiting factor for the biomass production of these species [28,30,31,35–37]. Birches on the other hand are moderately high consumers of water, and they have a higher drought stress resistance than willow [21]. As the plantation in Zwijnaarde is situated on a sandy soil, it can be expected that water availability was too low for an optimal growth of both poplar and willow. An additional explanation of the low biomass production results in Zwijnaarde is the relative large plot size of 400 m^2. Most other studies used much smaller plot sizes, and Pontailler et al. [38] stated that results from small plots are most

Table 6
Biomass production of European SRF plantations of willow

Species	Country	Soil type	pH	Management	Planting density (trees ha^{-1})	Rotation length (y)	Biomass production (t DM ha^{-1} yr^{-1})	Reference
1[a]	D	Sand	7.2–7.7	F	8333	4	2.3[a]	[22]
1	D	Sand	n.i.	F	8333	5	2.4[b]	[30]
1	D	—[c]	n.i.	None	16,667	5	2.7[c]	[30]
1	S	Clay	5.5–6.2	W, F	10,000	C+4	2.8[d]	[18]
1	D	Sand	n.i.	W, F	16,667	5	3.1[e]	[30]
1	S	Clay	5.5–6.2	W, F	15,000	C+4	3.4[f]	[18]
1	D	Sand	n.i.	None	8333	5	3.4	[30]
1	B	Sand	4.5	None	20,000	4	3.4	This study
1	D	Sand	n.i.	F	16,667	5	4.1[g]	[30]
1	S	Clay	5.5–6.2	W, F	20,000	C+4	4.4[h]	[18]
1	S	Clay	5.5–6.2	W, F	25,000	C+4	4.5	[18]
1	S	Clay	5.5–6.2	W, F	20,000	C+4	4.5	[18]
1[i]	S	Clay	6.5	W, F	20,000	4	5.8[i]	[20]
1[j]	S	Clay	6.5	W, F	20,000	4	9.5[j]	[20]

All results are for studies of *Salix viminalis* clones (code 1); country code B, Belgium; D, Germany; S, Sweden; management code W, weed control; F, fertilizers; rotation length, C means coppiced after establishment year; n.i., no information.
[a]Mean of two clones.
[b]Minimum of 12 clones.
[c]Maximum of 12 clones.
[d]Mean of two sites.
[e]Mean of three fertilizer treatments.
[f]Mean of four planting designs.
[g]Mean of three fertilizer treatments.
[h]Mean of six planting designs.
[i]Mean of eight fertilizer treatments.
[j]Mean of three planting designs.

probably overestimating the real production potential of poplar.

4.5. Reflections towards the establishment of SRF plantations in Flanders

The fields that will become available for SRF in Flanders will be marginal for agriculture production, as is the case in Germany [30]. As such, the site in Zwijnaarde demonstrates fairly well the biomass production that can be expected on these fields in the future. Birch can be considered as a very interesting alternative for the establishment of SRF plantations, as this species has a high adaptability to poor- or medium-quality soils. A rotation period of 8–12 years, combined with sowing birches instead of planting, seems promising for higher biomass productions in SRF plantations of this species [21]. Further research is needed to test this hypothesis. If poplar is used, a multiclonal plantation structure should be preferred, as this diminishes the risk on severe disease attacks [39].

In our plantation, neither weed control nor fertilizers were applied. Although the effects of these cultural activities on biomass production are ambiguous, it can have had a negative effect on the biomass production. On the other hand, avoiding the use of herbicides, pesticides and fertilizers averts environmental hazards as groundwater pollution by leaching of nitrogen [31,32,34]. Moreover, lower (or no) fertilisation and decreased (or no) use of herbicides and pesticides can enhance the diversity of both fauna and flora populations in SRF plantations [40–42].

5. Conclusion

Biomass production results for birch, maple, poplar and willow found in this study were in the lower range of results from other European studies. The low production for poplar and willow in Zwijnaarde was mainly caused by the limiting soil characteristics, as the combination of a low pH and a sandy soil, implying a suboptimal water availability, are not favourable for the growth of these two species. The low production of birch was mainly attributable to the rotation length of only 4 years and the low planting density in comparison to other experiments. An enhanced mean annual biomass production can be expected for this species when the rotation length and the planting density are increased. Because of the high water consumption of poplar and willow, and the sensitivity of especially poplar to different types of diseases, birch seems to offer an interesting alternative for SRF plantations in Flanders.

However, to gain optimal profit from all functions of SRF plantations, including soil water protection and provision of a (temporary) habitat, it is important that indigenous species, suited to the site, are chosen, and that as less herbicides and fertilizers as possible (by preference: none of them) are applied. In addition, multiclonal

plantations offer a better protection against severe pathogen or disease attacks than monoclonal sites, and should therefore be preferred.

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